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13. ABSTRACT (Maximum 200 words) The objectives of this research are to develop a comprehensive understanding of extreme floods and the storms that produce them and to dramatically improve the capability for monitoring extreme rainfall by remote sensing technologies, especially ground-based weather radar. Diagnostic studies have been completed for heavy rainfall events in the central Appalachians, Oklahoma, southeast Texas and Dallas, Texas. Detailed assessments of the WSR-88D rainfall algorithms have been completed.					
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1 Problem Statement and Objectives

The main objective of this research project was to develop a comprehensive understanding of extreme floods and the storms that produce them. A paired objective was to significantly improve the capability for monitoring extreme rainfall by remote sensing technologies, especially ground-based weather radar. Case studies of extreme storms and associated flooding formed the basis of this project. A common element of each study was the utilization of weather radar, an emerging technology which has broad application to military and civilian elements of the US Army mission. Observations from the DoD/DoC NEXRAD (Next Generation Weather Radar) network of WSR-88D (Weather Surveillance Radar - 1988 Doppler) radars provide unprecedented opportunities for monitoring storms that produce extreme flooding.

2 Summary of Major Results

Diagnostic studies of extreme rainfall and flooding comprise the core of the research carried out for this project. Major case study analyses were completed for rainfall and flooding events in the central Appalachians (Smith et al. [1996a]), Oklahoma (Bauer-Messmer et al. 1997), southeast Texas (Smith et al. [1999]) and Dallas, Texas (Smith et al. [1999b]). The Rapidan Storm and associated flooding in the central Appalachian region (Smith et al. [1996a]) and the Kickapoo Creek storm and flooding in the Coastal Plain of southeastern Texas are both events that reflect the most extreme rainfall and flooding conditions experienced in the continental United States. The Oklahoma (Bauer-Messmer et al. 1997) and Dallas, Texas events (Smith et al. [1999] and Baeck and Smith [1998]) are characterized by extreme rainfall rates over small areas and short time periods. These events are a special hazard to urban areas and other regions in which major landscape disturbance has occurred. Detailed assessments of the WSR-88D rainfall algorithms have been completed (Baeck and Smith [1998] and Smith et al. [1996b]). Analyses of case study events described in the following sections have provided an exceptional observational resource for development and testing of hydrologic models (especially the CASC2D model; see Ogden and Julien [1993]). Hydrologic model development and testing has been integrated into the project through the activities of students. As described in the Personnel section, research activities have had a significant impact on educational activities at

Princeton University. In the following sections, summaries and major conclusions are presented for the four case study events.

2.1 The Rapidan Storm of 27 June 1995

A storm system near the Blue Ridge of Virginia produced peak rainfall accumulations exceeding 600 mm in a 6 hour period during the morning and early afternoon of June 27, 1995 (Smith et al. [1996a] and Landel et al. [1999]). The peak flood discharge of $3,000 \text{ m}^3 \text{ s}^{-1}$ on the Rapidan River at a drainage area of 295 km^2 places this event on the envelope curve of flood discharge for the United States east of the Mississippi River. Observations of radar reflectivity factor and Doppler velocity made by the Sterling, Virginia WSR-88D (Weather Surveillance Radar - 1988 Doppler) were used for analyses of the storm. The temporal and spatial variability of rainfall were examined on a 1 kilometer grid scale and 6 minute time scale. Like many heavy rainfall events, storm motion played a key role in production of heavy rainfall for the Rapidan storm. Storm motion and storm evolution for the Rapidan storm were closely linked to topographic features at the scale of the ridges which extend southward from the Blue Ridge and delineate the Rapidan basin. Key elements of the storm environment included strong boundary layer winds directed upslope toward the Blue Ridge, weak upper level winds, high precipitable water values, and a near-saturated atmospheric column up to 6 km. An important element of storm structure was the low reflectivity centroid of the storm. This feature of the storm was related both to the exceptional rainfall rates of the storm and to underestimation of storm total rainfall by the operational WSR-88D precipitation products. Components of the atmospheric and land surface water budgets were derived. The cumulative discharge from the Rapidan River was $0.87 \times 10^8 \text{ m}^3$ (296 mm over the 295 km^2 catchment). The storm total precipitation for the Rapidan basin was $1.01 \times 10^8 \text{ m}^3$ (344 mm over the catchment). The precipitation efficiency of the storm, i.e. the ratio of storm total rainfall to atmospheric water vapor inflow, was approximately 90 percent. Observations developed in this study have been utilized by Professor Fred Ogden to develop a highly successful test implementation of the CASC2D modeling system.

The principal conclusions of analyses of the Rapidan Storm and associated flooding are the following:

1. The Rapidan storm of June 27, 1995 ranks among the most intense in the

central Appalachian region in terms of hydrologic and hillslope impacts. Peak six hour rainfall accumulations for the storm exceeded 600 mm. The estimated peak flood discharge of $3,000 \text{ m}^3\text{s}^{-1}$ on the Rapidan River at a drainage area of 295 km^2 ($10.17 \text{ m}^3\text{s}^{-1} \text{ km}^{-2}$) places this event on the envelope curve of flood discharge for the United States east of the Mississippi River.

2. The atmospheric environment of the storm bore striking similarities to other flash-flood producing storms, including the 1976 Big Thompson, Colorado storm. Notable similarities include strong upslope boundary layer winds, weak upper level winds, high precipitable water values, low reflectivity centroids and high precipitation efficiency.
3. Storm motion and evolution were closely linked with topography at the scale of the ridges which extend southward from the Blue Ridge and define the Rapidan basin. Orographic features played an important role in regulation of atmospheric moisture inflow to the storm.
4. The cumulative storm discharge of the Rapidan River was approximately 296 mm over the basin. The storm total precipitation was estimated from radar and rain gage observations to be 344 mm. The first storm on June 27 had a much lower estimated runoff ratio than the second, illustrating the important role of soil moisture storage for flood hydrology.
5. Atmospheric water vapor inflow to the storm, computed from VAD wind profiles, radiosonde humidity profiles and storm cross-sections derived from WSR-88D reflectivity observations, was slightly larger than net precipitation flux from the storm, indicating a precipitation efficiency of approximately 90 per cent.
6. Severe underestimation of rainfall by the operational WSR-88D algorithms was associated with the dominance of warm rain processes and the low echo centroid structure of the storm.
7. Reflectivity and Doppler velocity observations from the WSR-88D were of great utility in analyses of the Rapidan storm; the Doppler velocity observations were critical for estimating the atmospheric water budget of the Rapidan Storm.

2.2 The Kickapoo Creek Flood of 16-17 October 1994

Heavy rainfall and flooding visited the Coastal Plain of southeastern Texas in October 1994 resulting in 22 deaths and more than \$1 billion in damages (Smith et al. [1999] and Baeck and Smith [1998]). Record flooding occurred in the 1085 km² Spring Creek catchment, which received peak rainfall accumulations of more than 500 mm during a 12 hour period. Rainfall and flooding of greater magnitude occurred 100 km northeast of Spring Creek over Kickapoo Creek. The peak discharge of 2400 m³s⁻¹ in Kickapoo Creek at a drainage area of 148 km² places the event just below the Texas and United States envelope curve of peak discharge. Peak rainfall accumulations in Kickapoo Creek at time intervals from 15 minutes to 24 hours approached Texas and United States record values. The storms that resulted in flooding in Spring Creek and Kickapoo Creek were two components of one mesoscale convective system. The Spring Creek and Kickapoo Creek storms exhibited contrasts in storm structure, evolution and motion that are of fundamental importance for extreme flood response of drainage basins. The Spring Creek storm produced near-record spatial cloud-to-ground lightning frequencies over Spring Creek and large, cold cloud tops. The Kickapoo Creek storm had relatively low lightning frequency and a low echo centroid (LEC) structure in radar reflectivity profiles. The envelope curve of flood peaks in Texas is defined by floods from the Edwards Plateau, which is separated from the Texas Coastal Plain by the Balcones Escarpment. On 22 June 1997, flooding in Seco Creek, which is located in the Edwards Plateau 450 km southwest of Kickapoo Creek, resulted in a flood peak with comparable unit discharge to the October 1994 Kickapoo Creek flood. The Seco Creek and Kickapoo Creek storms provide two contrasting examples of how storm structure, evolution and motion can maximize flood peaks in a drainage basin. The storm properties that maximize flood peaks in Seco Creek and Kickapoo Creek are linked to drainage properties of the Edwards Plateau and Coastal Plain.

Major conclusions of this study are the following.

1. Two storm systems of contrasting properties produced extreme rainfall over southeastern Texas during a 14 hour period beginning 22 UTC 16 October 1994. Peak rainfall accumulations during the period exceeded 500 mm in the Spring Creek catchment and were approximately 600 mm in the Kickapoo Creek catchment. Rainfall accumulations at time periods from 15 minutes to 24 hours

were approximately 60 % of record values for the continental United States. The magnitude of rainfall rates from the Spring Creek storm exceeded 200 mm h^{-1} at 15 minute time scale (based on combined gage-radar analyses). For the Kickapoo Creek storm, 15 minute rainfall rates exceeded 270 mm h^{-1} (based on combined gage-radar analyses).

2. The unit discharge of $16.2 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ from the 148 km^2 Kickapoo Creek catchment places the event just below the Texas and United States envelope curve, but far above the envelope curve for the Texas Coastal Plain.
3. The Spring Creek storm, which formed along the boundary of a meso-high, exhibited classical manifestations of severe thunderstorms, including copious lightning, high cloud tops and a large cold cloud shield. Explosive growth of the Spring Creek storm around 4 UTC 17 October was associated with the most intense period of flood-producing rainfall. Individual convective elements within the Spring Creek storm moved rapidly to the northeast with the upper-level steering winds, tracking repeatedly over the central portion of the Spring Creek catchment.
4. The Kickapoo Creek storm contrasted sharply with the Spring Creek storm. The most important cloud property of the Kickapoo Creek storm was its Low Echo Centroid (LEC) structure. Associated storm properties included the relatively low cloud tops, small cloud shield and low lightning frequency. These cloud properties are consistent with very high precipitation efficiencies, as documented for the Rapidan and Big Thompson storms. Very small net storm motion was an important factor in producing catastrophic storm total rainfall accumulations. The region in which the Kickapoo Creek storm developed was in the path of a narrow ribbon of high-humidity boundary layer flow extending northward from the Gulf of Mexico.
5. The simultaneous occurrence of two extreme rainfall storms of contrasting cloud properties in close proximity is not unique to the October 1994 event. Similar situations have been documented for the Rapidan and Piedmont storms of 27 June 1995 in the Virginia Blue Ridge (Smith et al. [1996a]) and for the Fort Collins and High Plains storms of 28 July 1997 in Colorado (Landel et al. [1999]). The occurrence of two storms of contrasting cloud properties poses major difficulties for remote sensing technologies that are used to measure rain-

fall. Both satellite IR and radar algorithms are better suited to estimation of rainfall for severe thunderstorms like the Spring Creek storms, than for LEC storms like the Kickapoo Creek storms.

6. Storm structure and motion interact with drainage network geometry to control extreme flood response. Near-stationary storm motion over the Kickapoo Creek basin for a time period comparable to the maximum travel time for the basin leads to the extraordinary flood peak in Kickapoo Creek (see especially figures 13, 18 and 21). The Kickapoo Creek storm represents one model by which storm structure and motion can *maximize* peak discharge of a catchment (see Smith et al. [1996a] for related discussions of Probable Maximum Precipitation and Probable Maximum Flood analyses). The 22 June 1997 Seco Creek storm, for which storm motion is down catchment at a speed comparable to the basin runoff velocity, provides a second model for maximizing peak discharge of a catchment (see Ogden and Julien [1993] for related analyses).
7. The contrasts in extreme flood hydrology between the Edwards Plateau and Coastal Plain are clearly related to slope-controlled velocities of overland flow and open channel flow. An open question is whether spatial heterogeneities of extreme rainfall also play a major role in the geographic distribution of extreme floods. In particular, the role of orographic processes associated with the Balcones Escarpment warrants close examination.

2.3 Great Plains Thunderstorms of 7-8 July 1994

Measurement and forecasting of heavy rainfall requires interpretation of the small differences in the storm environment that distinguish a major flood-producing event from a relatively harmless storm system. The small differences in storm environment that lead to a heavy rainfall event in Oklahoma on July 9 1994 were examined in Messmer et al. [1997]. On 8 July 1994 two storm systems developed in close proximity to each other in central Oklahoma. One of the storms developed into a squall line and produced low storm total accumulations. The other was a slow-moving multicellular storm that produced storm total precipitation of more than 130 mm and flash flooding. The storms exhibited contrasting measurement errors in the operational WSR-88D rainfall products, with underestimation for the heavy rain event and overestimation for the squall line. The interactions of the synoptic, mesoscale and storm-scale processes for the 8 July event were examined in Messmer et al. [1997] through analyses of WSR-88D reflectivity and Doppler velocity observations, surface and upper air observations from the GEWEX-GCIP data set, and GOES observations of visible, IR and water vapor channels. This study provides a detailed characterization of the differences and similarities in the pre-storm environment that lead to flash flood episodes. Analyses also characterize storm-scale and mesoscale processes that play a major role in determining the accuracy of WSR-88D rainfall estimates.

Major conclusions of this study are the following.

1. Small differences in the atmospheric environment resulted in large differences in storm structure and evolution between the 8 July 1994 squall line in southern Oklahoma and the heavy rainfall event in northern Oklahoma.
2. Major differences in the two storms were reflected in the propagation speed and shape of the storms. The highly organized squall line produced relatively small point storm total accumulations (0 - 40 mm) over a large area. The less organized storm developed into a heavy rainfall event producing 100 - 130 mm and flash flooding.
3. The storms exhibited a variety of similar storm-scale features. The temporal evolution of rainfall flux and rain area were similar. Both storms had an echo centroid height of 7 km (contrast with Rapidan and Kickapoo Creek storms described in previous sections). Both storms had peak reflectivity values between 64 and 68 dBZ.

4. The storms differed markedly in internal organization. The squall line was dominated by long-lived meso(anti)cyclones, but the heavy rainfall event showed only short-lived shallow vortices. The heavy rainfall event moved at 30-40 km h^{-1} and the squall line moved at 50 km h^{-1} , with peak speeds of 100 km h^{-1} .
5. The operational WSR-88D rainfall algorithms provided rainfall estimates with contrasting measurement errors for the two storms. Underestimation by approximately 16 % was observed for the heavy rainfall event; overestimation of 19 % was observed for the squall line. The presence of hail imposed the most significant limitations on WSR-88D rainfall estimation accuracy for the two storms (see also the summary of the Dallas Hailstorm in the following section).
6. The WSR-88D rainfall estimates resolved heavy rainfall at space and time scales that are much finer than those resolved by the GCIP/GIST rain gage network. Analyses of this study clearly indicate that rain gage networks, even relatively dense networks like the GCIP/GIST network, can not resolve rainfall variability that is crucial for flash flood production.

2.4 The Dallas Hailstorm of 5 May 1995

The Dallas Hailstorm resulted in 16 deaths due to flash flooding and more than \$1 billion in property damage during the evening of 5 May 1995 (Smith et al. [1999b] and Baeck and Smith [1998]). Rainfall analyses using WSR-88D reflectivity observations and special mesonet raingage observations from Dallas show that catastrophic flash flooding resulted from exceptional rainfall rates at 5 - 30 minute time scale. The conditions under which the Dallas Hailstorm produced extreme rainfall rates were examined using WSR-88D reflectivity and Doppler velocity observations. The spatial structure of extreme rainfall rates was closely linked to supercell structure. Extreme rainfall rates occurred during the dissipating portion of the storm life cycle. Peak discharge for Turtle Creek in downtown Dallas approached the Texas envelope curve at 30 km^2 scale. The significance of supercell thunderstorms for the climatology of extreme short time-increment rainfall rates is examined. The Orlando Hailstorm provides a second example of a supercell storm producing extreme rainfall rates over a dense rain gage network. These storms represent a special hazard to urban regions. Significant rainfall measurement problems arise for supercell thunderstorms, both from conventional gage networks and weather radar. Hydrologic response to the storm in the Dallas metropolitan area illustrates the role of short-term rainfall rate and storm structure for flash flood response.

1. The Dallas Hailstorm resulted in 16 flash flood deaths in the Dallas metropolitan area and more than \$1 billion in property damages over the Dallas Fort Worth metroplex. The peak storm total rainfall of 120 mm was not exceptional for Texas; rainfall rates at 1 - 15 minute time intervals, however, nearly doubled the 100 year return interval values for the region. Catastrophic flood damages were due to the extreme 1 - 15 minute rainfall rates in an urban setting.
2. The storm responsible for the flood deaths and damage in Dallas was a supercell thunderstorm. These storms have been examined in previous research for their role in producing tornados and other manifestations of severe weather. They have largely been dismissed as agents of extreme flood-producing rainfall. Based on analyses of the Dallas Hailstorm and other supercell thunderstorms (Smith et al. [1999]), it is concluded that supercells are likely a significant contributor to the climatology of extreme rainfall rates at 1 - 30 minute time scale for many regions of the United States.

3. Fundamental rainfall measurement problems exist for storms like the Dallas Hailstorm. Measurements from conventional radar are quite useful, but also fundamentally limited in estimating extreme rainfall rates due to problems associated with hail contamination. Conventional rain gage networks do not sample supercell rainfall at relevant space and time scales. Radar polarimetric measurements provide a promising avenue for overcoming the hail problem. These methods are being considered for implementation in the DoD/DoC network of WSR-88D radars.

3 Publications

Baeck, M. L. and J. A. Smith, Estimation of heavy rainfall by the WSR-88D, *Weather and Forecasting*, 13, 416 - 436, 1998.

Bauer-Messmer, B., J. A. Smith, M. L. Baeck, and W. Zhao, Heavy rainfall: contrasting two Great Plains thunderstorms, *Weather and Forecasting*, 12(4), 717 - 730, 1997.

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4 Personnel

Personnel supported during this period include Professor Jim Smith, Bettina Bauer-Messmer (post-doctoral researcher), Paula Sturdevant-Rees (graduate student), Alberto Tapia (graduate student) and Julia Egorova (graduate student). Ms. Sturdevant-Rees received her PhD degrees during the course of the project. She will assume a faculty position at the University of Massachusetts in September 1999. Mr. Tapia received his MS degree. Four undergraduate students were supported during the project, Charlie Stock, Matt Rutherford, Gregoire Landel and Justin Niedzialek. All have pursued graduate study. Mr. Stock received a MS degree from Stanford and is currently pursuing his PhD at MIT. Mr. Rutherford is pursuing a PhD at Colorado State University. Mr. Landel is a graduate student at MIT (his senior thesis research has been accepted for publication in *Journal of Geophysical Research*; Landel et al. [1999]). Mr. Niedzialek will enter the graduate program at the University of Connecticut in September 1999 to study under Professor Fred Ogden. Senior thesis research by Mr. Stock and Mr. Niedzialek centered on numerical modeling studies utilizing the CASC2D modeling system (Ogden and Julien [193]). Dr. Sturdevant-Rees has also been heavily involved in translating the observational resources developed in this project into an environment for testing the performance of the CASC2D modeling system.

Professor Smith received the Princeton University Engineering Council Teaching Award in 1997 for his class Environmental Fluid Dynamics. The course utilized the Watershed Modeling System (WMS), which was developed under the direction of the Waterways Experiment Station, and the CASC2D modeling system. Research carried out as a part of this project played a significant role in enhancing the quality of the course.

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Baeck, M. L. and J. A. Smith, Estimation of heavy rainfall by the WSR-88D, Weather and Forecasting, Weather and Forecasting, 13, 416 - 436, 1998.

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